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REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SEMIANNUAL STATUS REPORT #17

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

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November 1, 1991 through April 30, 1992

Submitted by

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(NASA-CR-190211) LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES Semiannual Status Report No. 17, 1 Nov. 1991 - 30 Apr. 1992 N92-26438

Unclas
G3/91 0084150

TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Fahd and Steffes (1992), under Grant NAGW-533, have shown that the opacity from gaseous SO_2 under simulated Venus conditions can be well described by the Van Vleck-Weisskopf lineshape at wavelengths shortward of 2 cm, but that the opacity of wavelengths greater than 2 cm is best described by a different lineshape that was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements <u>and</u> to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identify and abundance profiles of constituents in those planetary atmospheres.

A. Laboratory Measurements

An important source of information regarding the Venus atmosphere is the increasing number of high spatial resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater et al., 1991). Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1991), with newly conducted Magellan radio occultation experiments (Steffes et al., 1991), and with our longer wavelength emission measurements (Steffes et al., 1990), will provide new ways for characterizing temporal and spatial variations in the abundance of both gaseous H_2SO_4 and SO_2, and for modeling their roles in the subcloud atmosphere. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous and liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981), no measurements have been made at shorter wavelengths. As a result, we conducted laboratory measurements of the 13 cm, 1.35 cm, and 3.2 mm opacity of gaseous SO_2. These measurements and their applications have been described in a paper by Fahd and Steffes (1992). Likewise, we recently completed laboratory measurements of the millimeter-wave dielectric properties of liquid H_2SO_4 in order to model the effects of the opacity of the clouds of Venus on its millimeter-wave emission spectrum (Fahd and Steffes, 1991a). The final experiment needed for proper interpretation of the

Venus millimeter-wavelength continuum is laboratory measurement of the opacity of gaseous H_2SO_4. We have recently completed such measurements. (See Section II of this report). In the remainder of the current grant year (ending October 31, 1992) we will complete development of a formalism for computing the millimeter-wave opacity of gaseous H_2SO_4, and apply it to our millimeter-wavelength radiative transfer model for Venus, which is described in Fahd and Steffes (1992). Already this work has shown that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the lower Venus atmosphere.

B. Magellan/Venus Radio Occultation Experiment

We have also been successful in this grant year in conducting a radio occultation experiment with the Magellan Spacecraft (see Steffes et al., 1991). This is the first atmospheric work conducted with Magellan and the atmosphere was probed to deeper levels than was possible with the less powerful Pioneer-Venus Orbiter radio transmission system. This experiment was conducted on October 5, 1991, and consisted of three entry occultation experiments. A description of this experiment is included in Section III of this report. This successful demonstration has shown the feasibility of using the Magellan spacecraft to provide highly accurate atmospheric refractivity and absorptivity profiles, which in turn, can be used to determine profiles of temperature, pressure, and gaseous H_2SO_4 abundance in the Venus atmosphere. We intend to use future Magellan radio occultation data as part of an integrated multi-spectral analysis of Venus atmospheric data.

II-MEASUREMENT OF THE OPACITY OF GASEOUS SULFURIC ACID (H_2SO_4) AT W-BAND (94.1GHZ)

A-Motivation

As discussed in previous reports, a complete understanding of the millimeter-wavelength emission from Venus requires an accurate determination of the opacities of the major absorbers in the Venus atmosphere. Recent observations of the millimeter-wave emission from Venus at 112 GHz (2.6 mm) have shown significant variations in the continuum flux emission (de Pater et al., 1991) which may be attributed to the variability in the abundances of absorbing constituents in the Venus atmosphere. Such constituents include gaseous H_2SO_4, SO_2, and liquid sulfuric acid (cloud condensates). Recently, Fahd and Steffes (1991a) have shown that the effects of liquid H_2SO_4 and gaseous SO_2 cannot completely account for this measured variability in the millimeter-wave emission of Venus. To fully understand potential sources of this variation, one needs to study the effects of gaseous sulfuric acid on the millimeter-wave emission of Venus.

Unfortunately, little (if any) laboratory work has been performed to measure the opacity of gaseous H_2SO_4 at millimeter-wavelengths for Venus-like conditions. In addition, the simple extrapolation of the microwave opacity of H_2SO_4 measured by Steffes (1985,1986) to higher frequencies is not straightforward and could lead to erroneous results.

To investigate the role of gaseous H_2SO_4 in the atmosphere of Venus, we have measured the opacity of gaseous H_2SO_4 in a CO_2

atmosphere at 550, 570, and 590 K from 1 to 2 atmospheres total pressure at 94.1 GHz. This work represents the first time that a measurement of the millimeter-wave opacity of a H_2SO_4/CO_2 gaseous mixture has been conducted for Venus-like conditions. We have also developed a modeling formalism to calculate the expected opacity of this gaseous mixture at other frequencies based on our measured results and the results reported by Steffes (1985,1986). Comparisons between the measured and the theoretically derived opacities of H_2SO_4/CO_2 mixture are also presented.

B-Laboratory Configuration

The experimental system used to measure the millimeter-wave opacity of gaseous H_2SO_4 in a CO_2 atmosphere consists of two major subsystems: The planetary atmospheric simulator and the millimeter-wave subsystem as diagrammed in Figure 1.

The planetary atmospheric simulator subsystem consists of a glass cell (which contains the gaseous mixture), two pressure gauges, a thermocouple display unit, a CO_2 tank and an oil diffusion vacuum pump. In this subsystem, the glass cell (length=27") is placed into a temperature controlled oven with a maximum temperature of 600 K. The temperature of the oven is electronically controlled, with a temperature variation of less than ± 5 K. A calibrated thermocouple unit is inserted into the glass cell in order to display the system's temperature. Liquid sulfuric acid is deposited into a custom made flask prior to the start of the measurements. The pressure and vacuum status of the planetary atmospheric subsystem are monitored via two gauges. Gauge

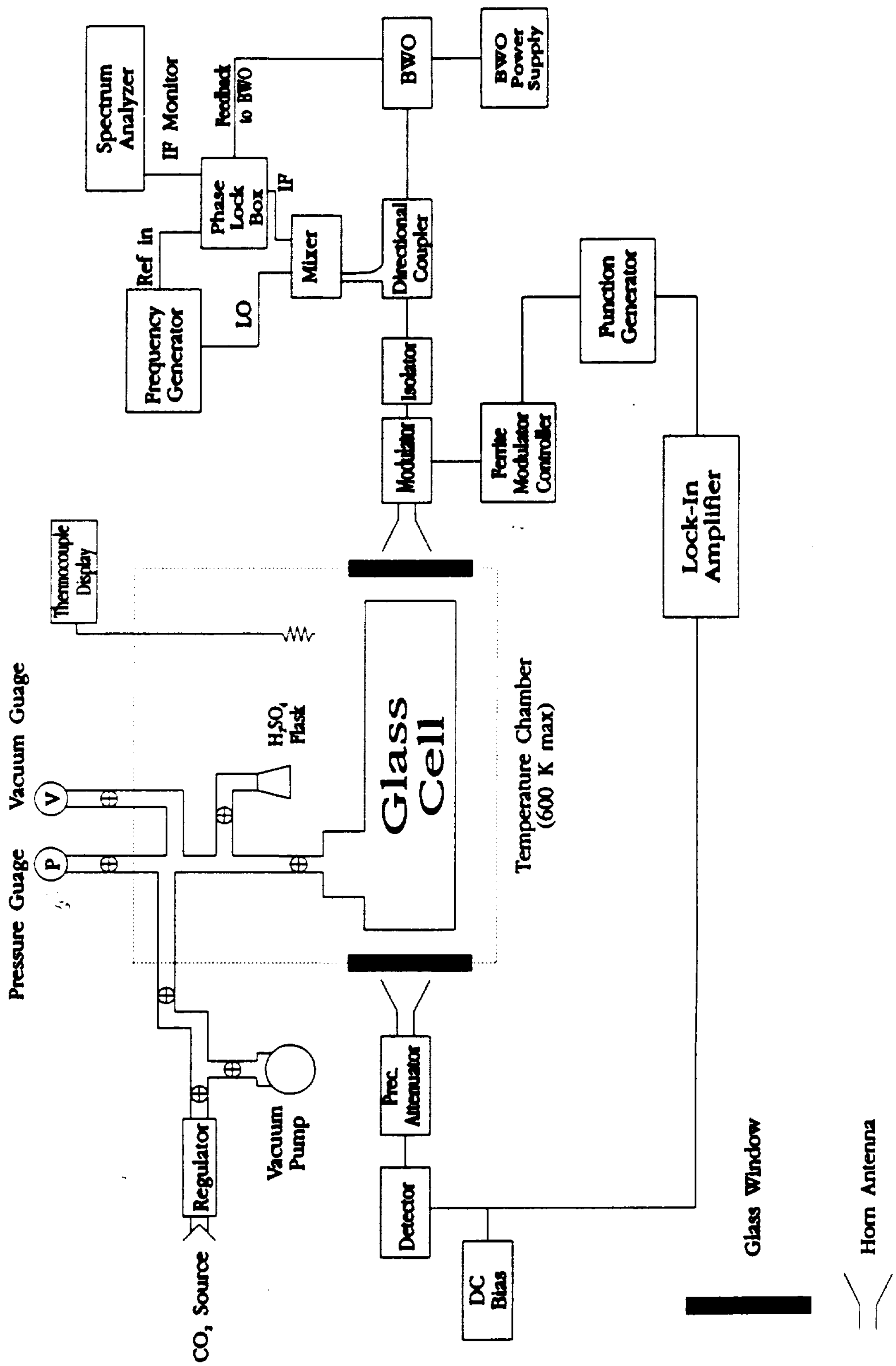

Figure 1 Block diagram of the atmospheric simulator as configured for measurements of the millimeter-wave absorption of gaseous H_2SO_4 under Venus atmospheric conditions at 94.1 GHz.

P (0-80 psig) with a display resolution of 1 psig and an accuracy of ± 3 psig is used to measure the internal pressure of the glass cell resulting from the introduction of the H_2SO_4/CO_2 gaseous mixture into the system. Gauge V is a thermocouple vacuum gauge that is able to measure pressures between 0-800 Torr with 1 Torr display resolution and an accuracy of 1% of full scale. It is used to monitor the vacuum status of the glass cell. Two Pyrex-66 glass windows are installed on the two sides of the oven to allow the propagation of the electromagnetic energy. A network of 3/8" stainless-steel tubing and valves connect the components of the planetary atmospheric subsystem so that each component may be isolated from the system as necessary. An oil diffusion pump is used to evacuate the glass cell prior to the introduction of the gaseous mixture.

The millimeter-wave subsystem (also shown in Figure 1) consists of a Siemens backward wave oscillator (BWO) powered by a MicroNow power supply. The BWO is electrically isolated from the waveguide apparatus by use of a polyester sheet and nylon screws on the waveguide flange of the BWO. (this is necessary to insure phase locking stability). Enroute to the glass cell, the signal is first sampled by a 10dB directional coupler. The sampled signal passes into a harmonic mixer as part of the phase locking system. The majority of the signal goes on through an isolator, which prevents reflections to the BWO, and is then electronically chopped by a ferrite modulator before entering the cell. The received power is detected by a schottky barrier point contact diode detector at 94 GHz. Power changes are measured as voltage changes at the detector. In order to give the detector the most linear response, the diode is biased with a current of 10 mA. The detector's output is measured with a lock-in amplifier where the modulation reference comes from a function generator which drives the ferrite switch. The modulation frequency is 100 Hz. The output of the lock-in amplifier is fed into a digital voltmeter.

Phase locking stabilizes the frequency output of the BWO. The -10dB port of the directional coupler feeds the BWO output into the harmonic mixer where it is heterodyned with the local oscillator (LO). A synthesized signal generator (2-18 GHz) serves as the LO and as the reference signal for the phase- locked loop. The intermediate frequency (IF) from the mixer is fed into the phase detector. The phase-locked loop functions only when the LO harmonic is below the BWO frequency, i.e., setting the LO to 9.368 GHz gives 9.368 GHz x 10= 93.680 GHz + 420 MHz IF = 94.1 GHz. An IF monitor output on the phase detector allows viewing the locked waveform with a spectrum analyzer.

In order to minimize the effect of any reflections from the cell wall, the radius of the cell must be chosen greater than the radius of the first Fresnel zone (the Fresnel zone is defined as that volume surrounding a ray path through which another ray can travel and arrive at the receiver having travelled no more than 1/2 wavelength farther than the primary ray; Bullington, 1957). Thus, it follows that

$$R_c > \left[\frac{\lambda r}{2}\right]^{1/2} \quad , \tag{1}$$

where R_c is the radius of the cell, λ is the wavelength (in this case 3 mm), and r is the separation distance between the two horns (1 m). Using the above equation, a minimum cell radius of 1.52" is required. A glass cell with a radius of 2.5" is used in the experimental setup.

C-Measurement Procedure

The measurement of the millimeter-wave opacity of gaseous H_2SO_4/CO_2 can be summarized as follows: The oven is first heated to the desired temperature. Once the desired temperature is reached, the glass cell is evacuated. By using gauge V as a vacuum monitor, we are able to check the status of the glass cell in order to insure that no major leaks are present. Although the chamber is not leak proof, we are able to maintain a leak rate within the system of less than 1 Torr/hour. The variable attenuator is then set to a predetermined attenuation and the resulting detector voltage is recorded. (The millimeter-wave subsystem is usually turned on for a period of ten hours prior to the beginning of the experiment. This extended time period allows the BWO to warm up and become more stable.) Next, the valve connecting the H_2SO_4 flask and the glass cell is opened allowing the sulfuric acid vapor to equilibrate with the evacuated glass cell. Once equilibrium is reached, the flask's valve is closed and a visual check is made to verify that the remaining liquid acid is clear. Gaseous CO_2 is then introduced in the system at a slow rate so as not to cause any condensation. When the total internal pressure (measured by gauge P) reaches 2 atm, the CO_2 tank is shut off and the two gases are allowed to mix for a specified time period. The attenuation on the variable attenuator is then decreased until the output voltage is equal to the detector voltage of the evacuated glass cell. The opacity of the gaseous mixture can then be inferred from the change in the calibrated attenuator setting. The total internal pressure is then reduced to 1 atm and the measurement process is repeated. This approach has the advantage that the same gas mixture is used for the measurement at various pressures (at each temperature point). Thus, even though some uncertainties may exist due to the mixing ratio of the initial mixture, the mixing ratios at subsequent pressures will be the same, and the uncertainties for any pressure dependence will only be due to the accuracy limits of the absorptivity measurements and not to uncertainties in the mixing ratio.

D-Experimental Uncertainties

In general, the main source of experimental uncertainties in the transmission measurements is the fluctuation in the output power of the source. However, our system is phase locked so as to minimize frequency and output power deviations. Frequency stabilization due to the phase locking system is on the order of ± 20 KHz and power variation is less than ± .02 dB. In order to incorporate the effect of frequency and power fluctuation in our error bars, two measurements are taken for each data point and statistics are developed to compute the 1 σ variation in the measured absorptivity (the number of data points collected was limited due to the availability of some of the equipment).

Additional instrumental uncertainties include uncertainties in the measured pressure and temperature. In the case of pressure measurements, the accuracy was limited by the quality of the two pressure gauges used. The 0-800 Torr gauge has an accuracy of 1% of the full scale while the 0-80 psig gauge has an accuracy of ± 3 psig. The temperature accuracy of the thermocouple used was ± 5 K (temperature uncertainty is shown as horizontal error bars in Figure 2). The accuracy of the variable attenuator is also incorporated in our total uncertainties. The uncertainties due to the mixing ratio have been determined for the three temperatures used in our measurements. Using the expression developed by Spilker (1990) for mixing ratio accuracy, mixing ratios of 1.25% ± 0.13% ,0.87% ± 0.087% and 0.59% ± 0.06% are obtained at 590, 570, and 550 K respectively (in this calculation the partial pressure of H_2SO_4 is obtained from equation (2)). These mixing ratios uncertainties are also included in the vertical error bars shown in Figure 2.

Additional experimental uncertainties include the detector's noise which was characterized from variations in the measured output voltage. The resulting total uncertainties due to noise and instrumental uncertainties are shown in Figure 2 as ±1 σ variations about the mean.

E-Experimental Results and Theoretical Characterization of H_2SO_4 Absorption

Measurement of the opacity of gaseous H_2SO_4 in a CO_2 atmosphere has been performed at 94.1 GHz and at temperature of 550 K, 570 K, and 590 K. These temperatures were chosen so as to allow enough H_2SO_4 vapor in the glass cell. The experiment was conducted at total pressures of 2 and 1 atm for each temperature. For a specific pressure and temperature, the expected vapor pressure of H_2SO_4 can be computed by,

$$\ln p = 6.65 - \frac{6100}{T} \tag{2}$$

where p is the sulfuric acid vapor pressure (atm) and T is the temperature in K. Using the above expression, a mixing ratio of 1.23%, .87% and .59% occurs respectively at 590, 570 and 550 K.

The measured absorption (dB/km) of H_2SO_4/CO_2 at 94.1 GHz is shown in Figure 2 where it is plotted as a function of temperature for 2 and 1 atm. (note that the reported absorptions are normalized to their respective mixing ratios). Using the measured data, a best fit multiplicative expressions has been developed to predict the absorption of H_2SO_4/CO_2 at 94.1 GHz,

$$\alpha = 2x10^{11} p^{.98} q\, T^{-2.9} \qquad dB/km \tag{3}$$

where q is the H_2SO_4 number mixing ratio, P is the total pressure in atmospheres, and T is the temperature in Kelvins.

Although the developed expression is valid for the conditions at which the measurements were performed (i.e. 94.1 GHz), care must be taken when projecting the absorption of H_2SO_4 at frequencies far from 94.1 GHz. To accurately determine the expected absorptivity at other frequencies, we have used the Van Vleck-Weisskopf (VVW) formalism to calculate the opacity of the H_2SO_4/CO_2 gaseous mixture. In this formalism, the absorptivity due to a single resonant line, at frequency f, can be computed as per Townes and Schawlow (1955),

$$\alpha = \alpha_{max} f^2\ \nu_o^{-2}\ \delta\nu^2 \left[((\nu_o - f)^2 + \delta\nu^2)^{-1} + ((\nu_o + f)^2 + \delta\nu^2)^{-1} \right] \tag{4}$$

where f is the frequency in GHz, ν_o is the resonant line frequency,

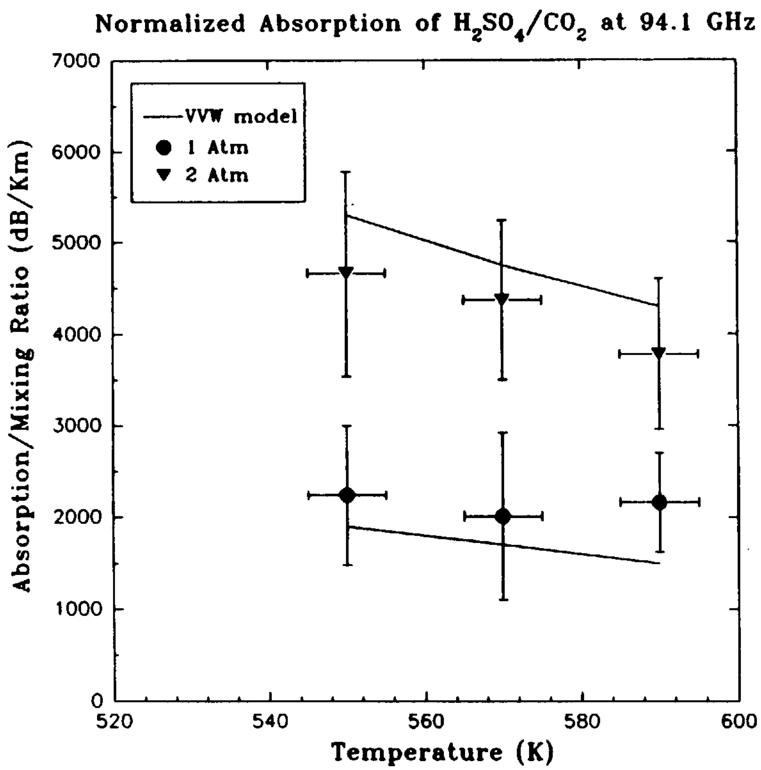

Figure 2 Laboratory measurements of the normalized absorptivity (dB/km) of gaseous H_2SO_4 in a CO_2 Atmosphere at 94.1 GHz. Solid curves are the theoretically calculated absorption from the VVW formalism.

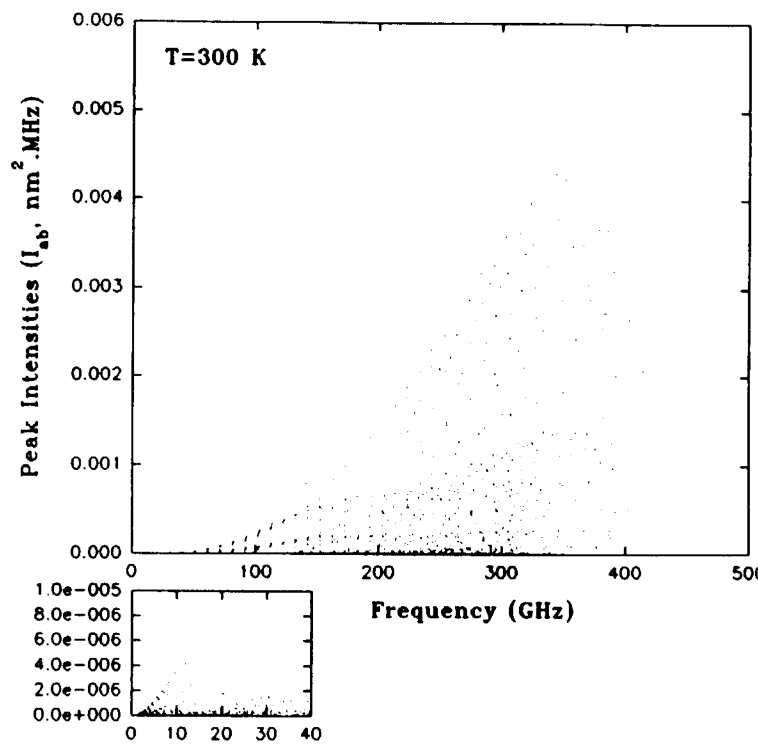

Figure 3 Diagram of the peak intensities at 300 K of the 2359 resonant lines used in the VVW formalism.

and $\delta\nu$ is the line width. In our VVW model, we totaled the contribution from 2359 resonant lines reported by Pickett et al. (private communication, 1991). These lines cover the frequency between 1.5 and 450 GHz. A graphical representation of the resonant lines and their respective line intensities, I_{ab}, are shown in Figure 3 along with an expanded view of the lines between 1.5 and 40 GHz.

In order to fully implement the VVW formalism, an appropriate broadening parameter, $\delta\nu$, must be determined. Previously, Janssen and Poynter (private communication, 1987) used a value of 3 MHz/Torr in their model (their model used a different set of resonant lines) but their results were inconsistent with the measured microwave absorptivity of Steffes (1985,1986). In addition, no measurements of the broadening parameter of H_2SO_4 by CO_2 have been reported. To solve this problem, we adjusted the broadening parameter in the VVW formalism so that the calculated opacity matches the measured absorptivity at 94.1 GHz and the microwave absorption at 2.24 GHz and 8.42 GHz reported by Steffes (1985). As a result, a broadening parameter of 1.55 MHz/Torr was found to fit the above data and seem to provide close agreement between the measured and calculated values of the absorptivity of H_2SO_4 in a CO_2 atmosphere.

A comparison between the calculated and measured opacities of H_2SO_4/CO_2 are shown in Figures 2, 4, and 5 where the discrete data points in Figures 4 and 5 are obtained from Steffes (1985). In Figure 4, the calculated absorption of H_2SO_4/CO_2 mixture at 2.24 GHz and temperatures of 564 and 575 K are compared with the previously

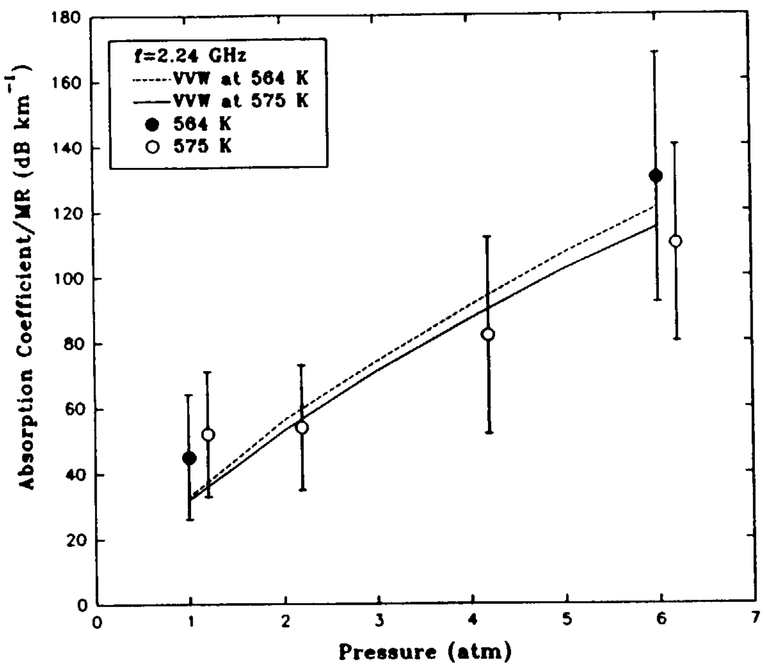

Figure 4 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985,1986) and the calculated absorption from the VVW formalism at 2.24 GHz.

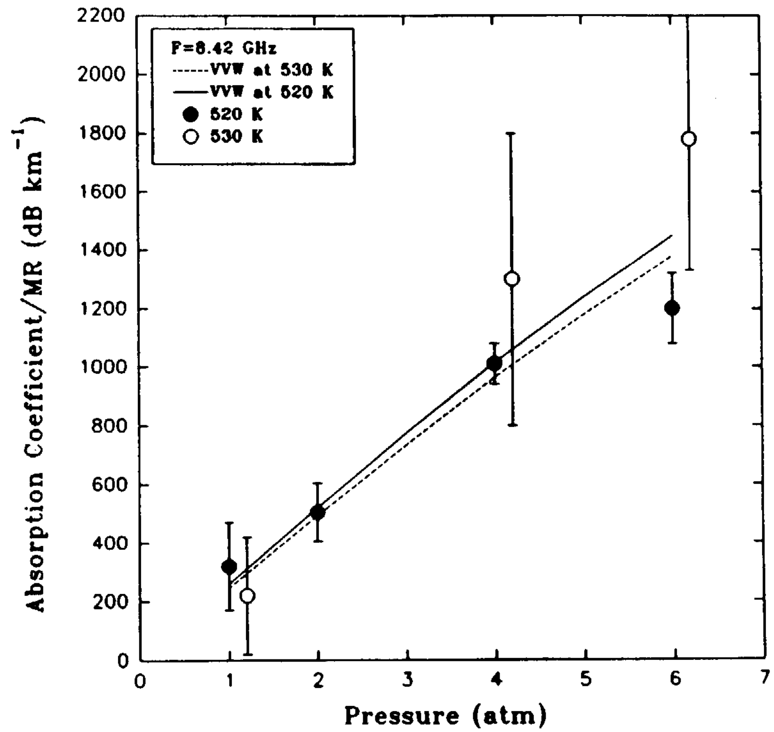

Figure 5 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985,1986) and the calculated absorption from the VVW formalism at 8.42 GHz.

published work. Similarly, Figure 5 shows the results at 8.42 GHz and temperatures of 550 and 520 K. A careful examination of these results indicates that the calculated opacities of H_2SO_4 using the VVW formalism with a broadening parameter of 1.55 MHz/Torr agree well with the measured microwave and millimeter-wave opacities of the gaseous mixture. This finding is quite important since it demonstrates for the first time that the VVW formalism can be used to accurately predict the opacity of H_2SO_4/CO_2 gas mixture over a wide frequency range. As a result, we can use the developed model to predict the opacity of H_2SO_4 at other specified conditions and in particular, we can employ the VVW formalism in our radiative transfer model to study the effects of this gaseous mixture on the emission from Venus.

III. RADIO OCCULTATION STUDIES OF THE VENUS ATMOSPHERE WITH THE MAGELLAN SPACECRAFT

Soon after the launch of the Magellan spacecraft (in 1989), it was suggested by P. Steffes of Georgia Tech, that Magellan could be used for radio occultation studies of the Venus atmosphere. Because of its larger antenna, the stronger transmitted signal could be tracked deeper into the Venus atmosphere, and the inferred quantities, such as the 13 cm and 3.6 cm absorptivity due to gaseous sulfuric acid could be determined to a much higher accuracy.

On May 7, 1991, we made a presentation at the Magellan Atmospheric Science and Contingency Workshop, and subsequently made the same presentation to the Magellan Project Steering Group, detailing the goals and required support for this experiment. The experiment was approved, and was conducted during three successive orbits on October 5, 1991. While data processing is not yet complete, the operational aspects of the experiment are highlighted in Appendix I, which was a poster paper presented at the 1991 AAS/DPS meeting (Steffes et al., 1992). This paper also describes the spacecraft maneuver required for this experiment. Later in this grant year, we will have access to the data in order to process it for the atmospheric parameters, particularly the microwave absorptivity, which is related to the abundance of gaseous H_2SO_4.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

At the beginning of the grant year, we published 2 papers in the Journal of Geophysical Research: Planets (special issue on Laboratory Research for Planetary Atmospheres). The first is entitled "Modeling of the Millimeter-Wave

Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3 Opacity" by Joiner and Steffes (1991a). The second is entitled "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)" by Fahd and Steffes (1991a). We have also had a paper accepted by the IEEE Transactions on Microwave Theory and Techniques entitled "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths," by Joiner and Steffes (1992) describing our observations of Jupiter at 1.4 mm, and the accompanying laboratory measurements of H_2S at that wavelength. It will be published this summer in a special issue on "Microwaves in Space," commemorating the International Space Year. Finally, we have had a paper accepted by Icarus describing our laboratory measurements of the microwave and millimeter-wave opacity of gaseous SO_2 in a CO_2 atmosphere. This paper is entitled "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO_2) under Simulated Conditions for the Venus Atmosphere," by Fahd and Steffes (1992).

Also, at the beginning of grant year (November 3 - November 8, 1991), we attended the annual DPS/AAS Meeting and the accompanying Third International Conference on Laboratory Research for Planetary Atmospheres, and presented 6 papers (Steffes et al., 1991; Fahd and Steffes, 1991a; Ragent et al., 1991; Fahd and Steffes 1991c; Jenkins and Steffes, 1991; and Joiner and Steffes, 1991). Reprints are included as Appendices.

Finally, as this research program has progressed, the number of graduating Ph.D.'s has increased. In the first half of this grant year, Joanna Joiner received her Ph.D. Copies of her thesis, entitled "Millimeter-Wave Spectra of the Jovian Planets" (Joiner, 1991) were forwarded to NASA in September 1991.

Similarly Jon M. Jenkins received his Ph.D. in March 1992. His thesis, entitled "Variations in the 13 cm Opacity below the Main Cloud Layer in the Atmosphere of Venus Inferred from Pioneer-Venus Radio Occultation Studies: 1978 - 1987" (Jenkins, 1992) was supported by the Pioneer Venus Guest Investigator Program and supplementally by the Planetary Atmospheres Program. Copies were forwarded to NASA in March. Finally, Antoine K. (Tony) Fahd is currently preparing his Ph.D. dissertation, entitled "Study and Interpretation of the Millimeter-Wave Spectrum of Venus."

V. CONCLUSION

In the remainder of this grant year (ending October 31, 1992) we will apply this new formalism for computing the opacity from gaseous H_2SO_4 to our radiative transfer model for Venus which we described in Fahd and Steffes (1992). Already this work has shown that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the Venus atmosphere. In fact, variations in the abundance of gaseous H_2SO_4 can explain the variations in the 2.6 mm Venus emission reported by dePater et al., (1991). In August, we plan to report on our work at the International Colloquium on Venus to be held in Pasadena. Similarly, we will present these results and additional results from the Magellan experiment at the October DPS/AAS meeting in Munich.

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VII. APPENDICES

APPENDIX I : Poster Paper Presented at the 1991 DPS/AAS Meeting

20.20-P RADIO OCCULTATION STUDIES OF THE VENUS ATMOSPHERE WITH THE MAGELLAN SPACECRAFT

P.G. STEFFES, J.M. JENKINS (GEORGIA INST. OF TECH.), R.S. AUSTIN, S.W. ASMAR (JPL/CALTECH), G.L. TYLER (STANFORD UNIV.), AND E.H. SEALE (MARTIN MARIETTA)

While primarily designed for radar studies of the Venus surface, the high radiated power (EIRP) from the Magellan spacecraft makes is an ideal transmitter for use in a bistatic radio occultation measurement of the refractivity and absorptivity of the Venus atmosphere. The experiment (conducted 10/5/91) involved transmissions at 2.3 GHz and 8.4 GHz (13 cm and 3.6 cm, respectively), and was performed during spacecraft ingress for 3 orbits. Since the stability of the spacecraft transmitter is critical for accurately determining the doppler shift and amplitude attenuation created as the ray penetrates the atmosphere, the spacecraft transmitter was locked to a 2.1 GHz uplink from DSS-43 (Tidbinbilla, Australia), which also received the signals. Because of the high gain of the spacecraft antenna, and the significant ray bending in the deep Venus atmosphere, a spacecraft tracking maneuver was designed to keep the spacecraft antenna pointed in the direction of the refracted ray path back to earth. This tracking maneuver, plus the high effective isotropic radiated power (EIRP) of the Magellan transmitter is expected to yield 3.6 cm refractivity and absorptivity profiles down to the 42 km altitude and 13 cm profiles down to the altitude of critical refraction (approximately 35 km), once the data is processed. It is also expected that the statistical uncertainties in the derived profiles will be significantly lower than those previously obtained, and will result in extremely accurate profiles of H_2SO_4 (g) abundance.

Figure 1

ATMOSPHERIC RADIO OCCULTATION MEASUREMENTS WITH MAGELLAN AT VENUS

GOALS: OBTAIN REFRACTIVITY AND ABSORPTIVITY PROFILES (13 cm and possibly 3.6 cm) TO LOWEST POSSIBLE ALTITUDES IN THE VENUS ATMOSPHERE IN ORDER TO BETTER CHARACTERIZE SPATIAL AND TEMPORAL VARIATIONS

USE ABSORPTIVITY PROFILES TO CHARACTERIZE ABUNDANCE AND DISTRIBUTION OF GASEOUS H_2SO_4 AND IDENTIFY SPATIAL AND TEMPORAL VARIATIONS OF SAME.

DEVELOP T-P PROFILES FROM REFRACTIVITY PROFILES AND CORRELATE VARIATIONS IN SUB-CLOUD T-P PROFILES WITH VARIATIONS IN H_2SO_4 ABUNDANCE, AND WITH MAPS MADE BY GALILEO NIMS.

ADVANTAGES OVER PIONEER-VENUS RADIO OCCULATION EXPERIMENTS:

MUCH HIGHER EIRP (EFFECTIVE ISOTROPIC RADIATED POWER) FROM MAGELLAN WILL RESULT IN PROFILES WITH SMALLER ERROR BARS AND WILL ALLOW PROBING MUCH DEEPER IN THE ATMOSPHERE. ITS IS EXPECTED THAT AT 13 CM, SIGNAL CAN BE TRACKED DOWN TO THE 35 KM ALTITUDE AND DOWN TO 42 KM AT 3.6 CM. THIS COMPARES WITH 42 and 54 KM, RESPECTIVELY FOR PIONEER-VENUS.

BECAUSE OF THE SHORTER ORBITAL PERIOD, SUCCESSIVE OCCULTATIONS WOULD ONLY BE SPACED BY ABOUT 3 HOURS, THUS "DECOUPLING" THE TIME VARIABILITY FROM THE SPATIAL VARIABILITY. (SEVERAL I.R. OBSERVERS HAVE REPORTED A LARGE FEATURE WHICH SEEMS TO CIRCLE VENUS EVERY 72 HOURS OR SO. WITH TWO OCCULTATION MEASUREMENTS MADE ONLY HOURS APART, THE SPATIAL EDGE OF SUCH A FEATURE MIGHT BE DETECTED.)

PIONEER VENUS WILL ENTER THE VENUS ATMOSPHERE NEXT YEAR.

SUPPORT REQUIRED:

DSN 70-METER ANTENNA (S-BAND UPLINK, 80KW; OPEN LOOP RECEIVER FOR S-BAND DOWNLINK; AND (AS AN OPTION), OPEN LOOP RECEIVER FOR X-BAND DOWNLINK)

SPACECRAFT TRACKING MANEUVER, SO AS TO KEEP HGA POINTED TOWARD THE LIMB OF THE PLANET (AND THUS THE RAY PATH BACK TO EARTH).

A GOOD CHARACTERIZATION OF THE TRACKING MANEUVER, SO THAT VARIATIONS IN RECEIVED AMPLITUDE DUE TO SPACECRAFT MOTION ARE NOT MISTAKEN FOR ATMOSPHERIC EFFECTS.

P.STEFFES

RADIOSCIENCE EXPERIMENT REQUIREMENTS

IMPLEMENTATION:
- NON-RSA ORBITS (MGN ORBITS 3212, 3213, & 3214)
- TURN BETWEEN TWO FIXED ATTITUDES
- NEARLY CONSTANT RATE OF 0.083°/SEC
- DURATION OF APPROX 180 SEC

SPACECRAFT:
- X-BAND DOWNLINK WITH HIGH-RATE MODULATOR OFF (X-BAND TELEMETRY LEFT ON)
- S-BAND DOWNLINK WITH TELEMETRY MODULATOR OFF
- RECORD S/C RECEIVED SNR
- RECORD S/C ATTITUDE ERROR DATA ON TAPE FOR MANEUVER RECONSTRUCTION

DSN:
- 70M STATION
- 80KWATTS S-BAND UPLINK (60 dB MARGIN AT MANEUVER START)
- OPEN LOOP RECEIVER TRACKING
- PERFORM TEST (RECORD S/C DOWNLINK WITH RADIOSCIENCE RECEIVERS) ON 19, AUGUST
- 5/6 OCT: RECORD BOTH POLARIZATIONS

NAV:
- POST-MANEUVER UPDATES TO PERIAPSIS CROSSING TIMES

ANCILLARY:
- NEED BOTH S AND X-BAND ANTENNA PATTERNS (AT LEAST SEVERAL CUTS)

FIGURE 3:
RADIOSCIENCE EXPERIMENT PROFILE
(MGN ORBITS 3212, 3213, & 3214 : 5OCT91 and 6OCT91)

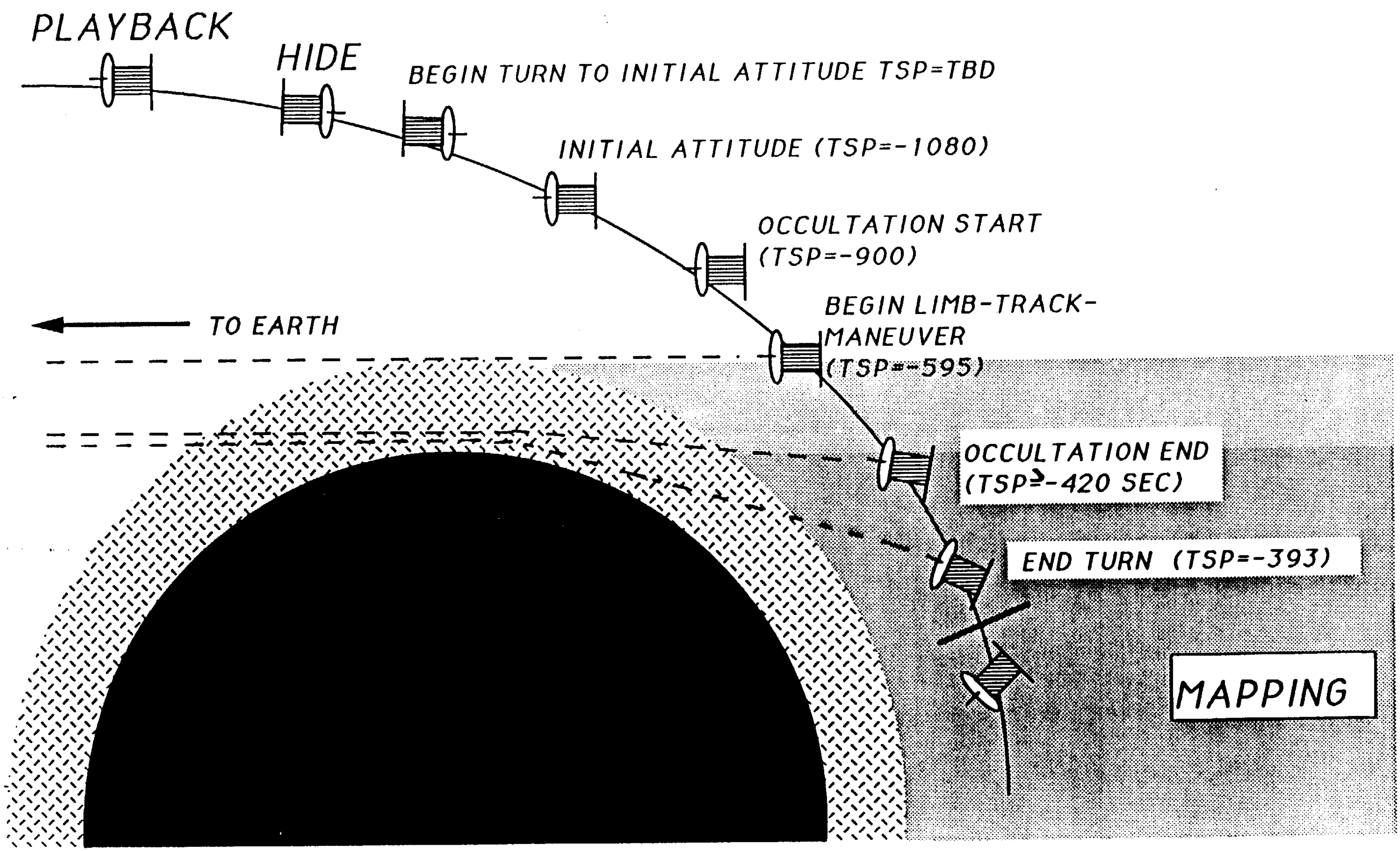


Figure 4: Predicted bending angle of ray (in radians) as a function of time at the receiving station

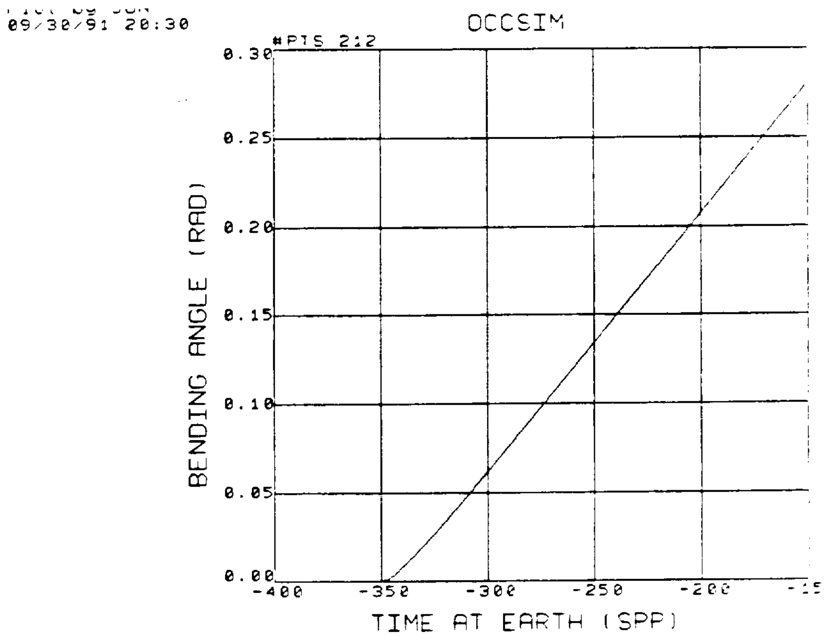


Figure 5: Antenna Pattern for Magellan at X-Band (3.6 cm). The narrowness of the beam requires that the spacecraft be re-pointed in order to keep the antenna directed toward the refracted path back to Earth.

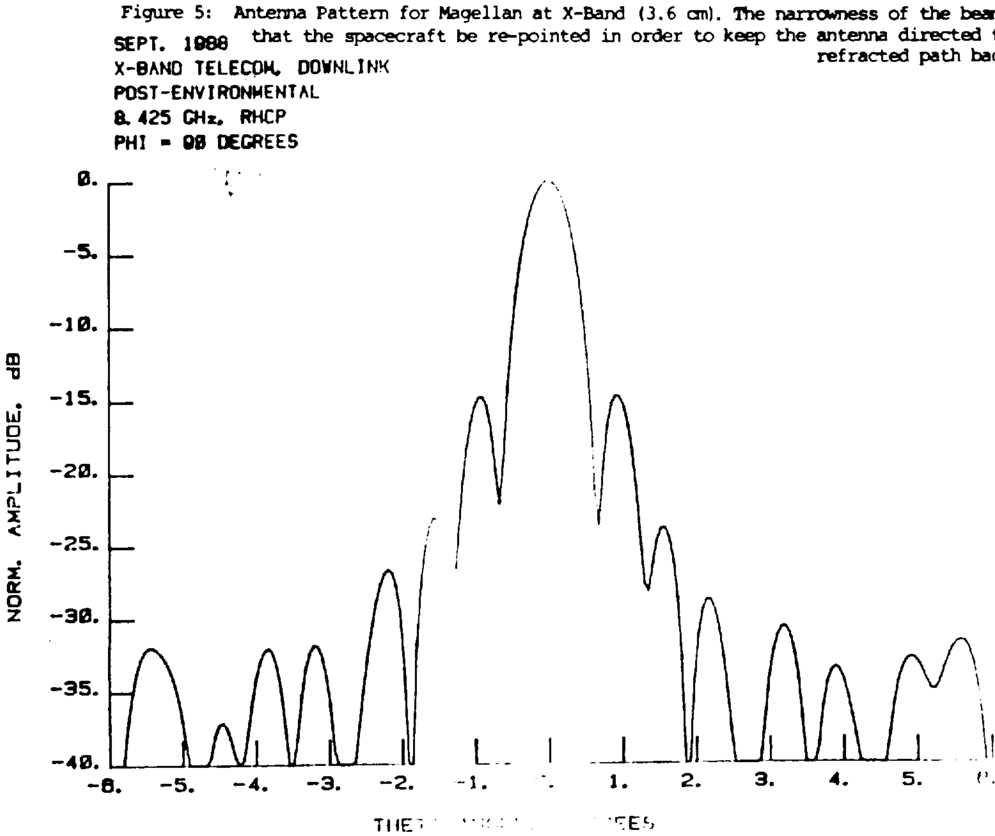
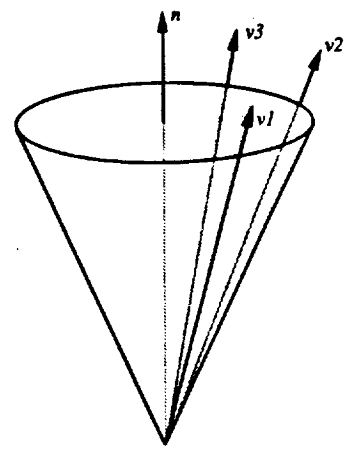


Figure 6a: Antenna tracking maneuver design using conical track

Preliminary Limb-Tracking Maneuver Design -- Earth Track Cone Determination



- In a plane, 3 points define a circle
- In space, 3 vectors define a cone
- We want the axis of a cone that "fits" the Earth image vectors well -- this will be the eigenvector for the rotation to scan the HGA through the vectors
- For simplicity, I'll define a cone using 3 hand-picked vectors (first, last, middle) -- don't want to derive a 3-D least-squares algorithm just yet...

Figure 6b: **Path Fit Error (Cross-Track) Over Time**

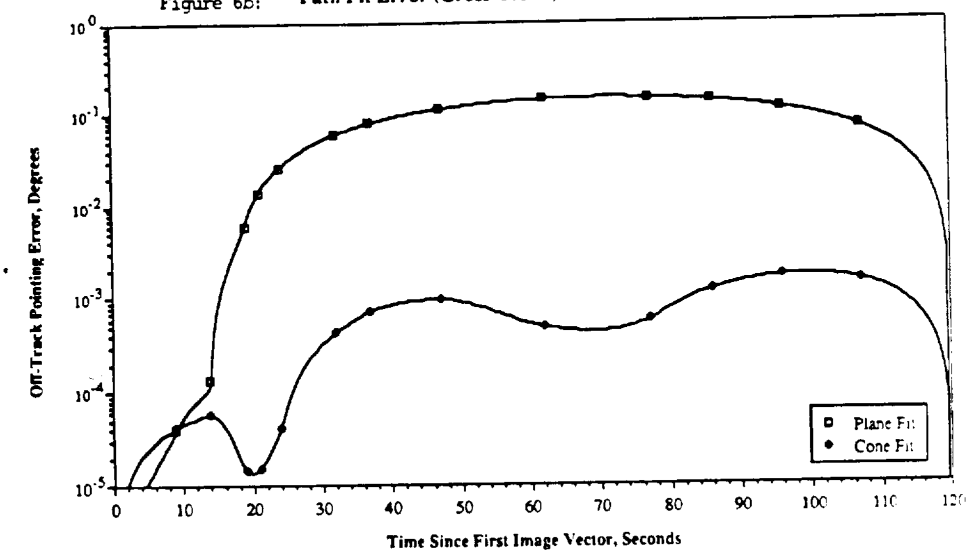


Figure 6c: Along-Track Pointing Error Over Time

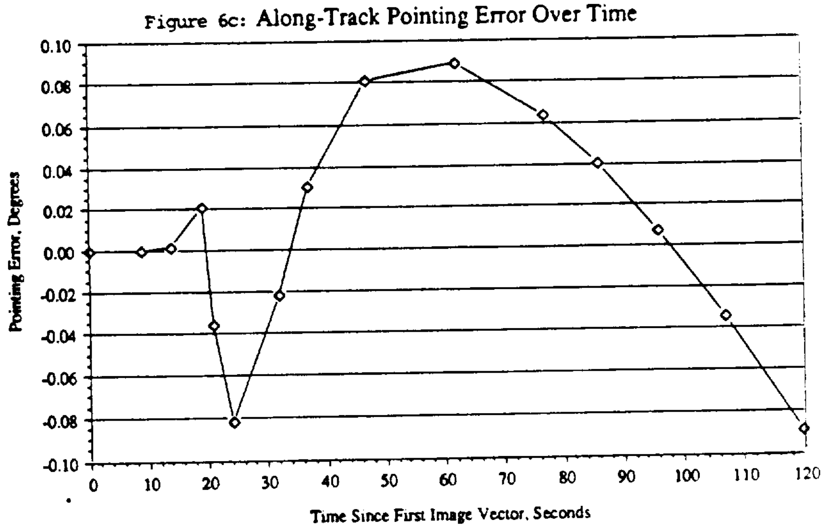
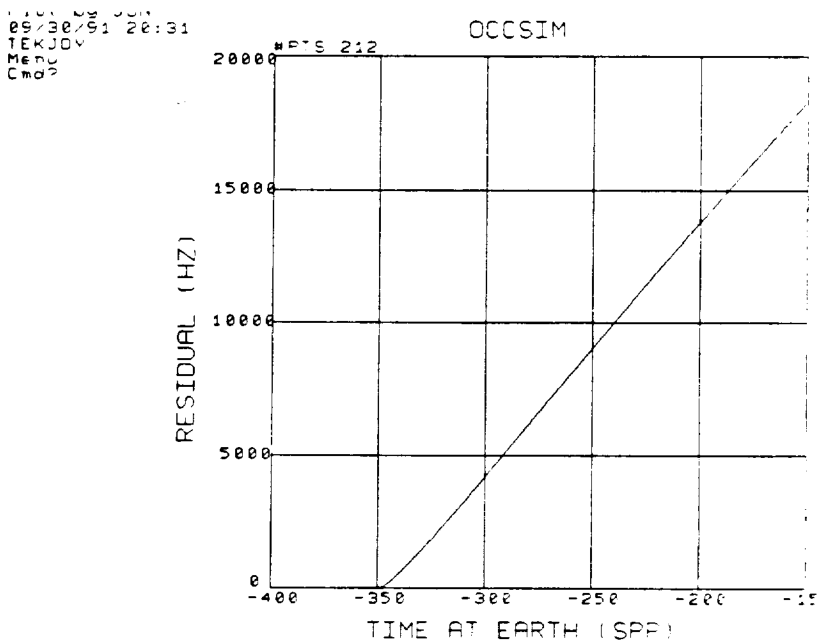
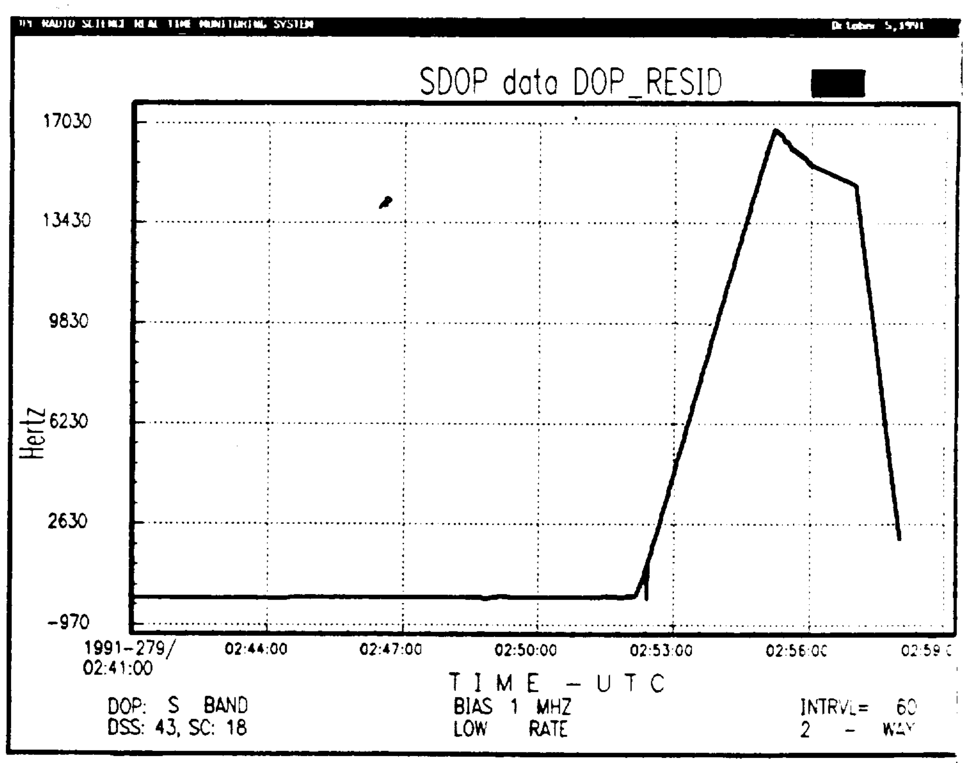


Figure 7: Excess doppler (in addition to that expected from normal motion of spacecraft and earth) encountered during radio occultation experiment as a function of time at the receiving station (Note: SPP is short for Seconds Past Periapsis)





7b - S-Band Doppler actually measured -

Figure 8: Solid line: Relative amplitude of received signal as a function of time at the receiving site. (predicted)
Upper dotted line: Portion of amplitude reduction due to atmospheric absorption (predicted)
Lower dotted line: Portion of amplitude reduction due to refractive defocussing (predicted

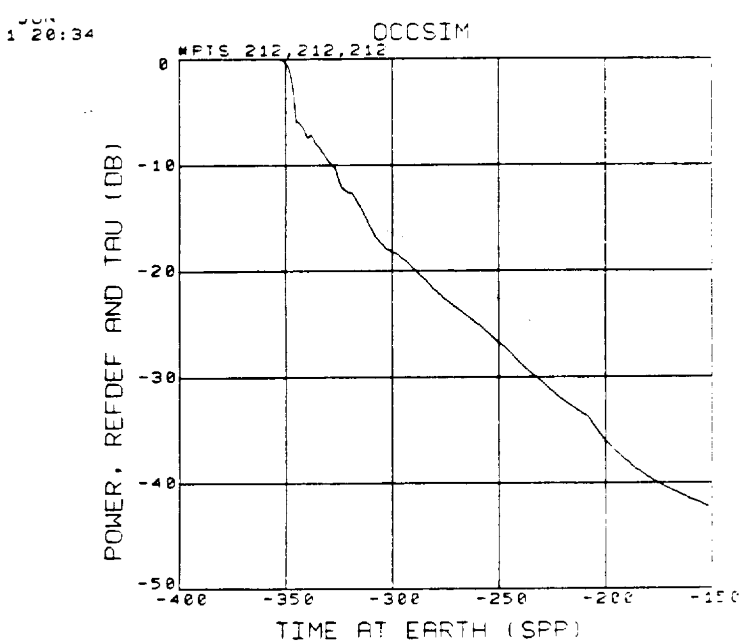


Figure 9: Radius of deepest ray penetration versus time of reception at earth station.

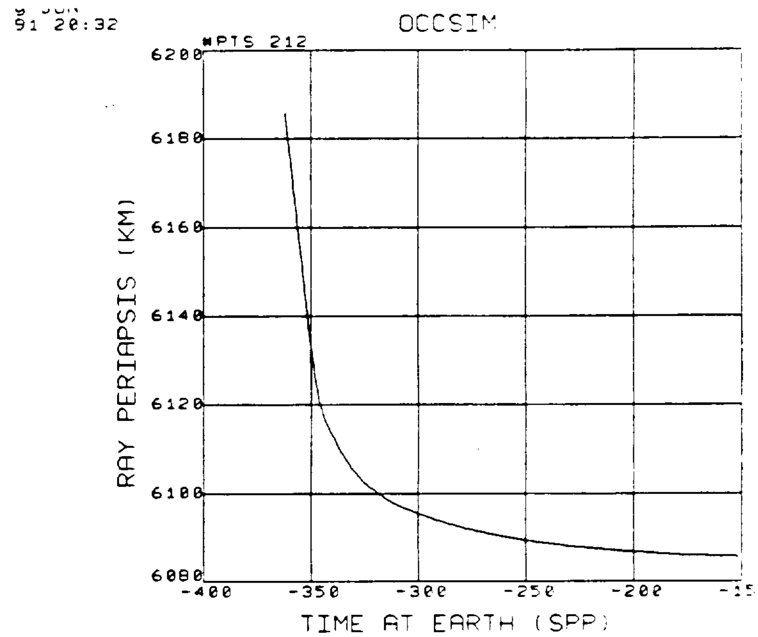


Figure 10: Radius of deepest ray penetration versus time of reception at earth station, expanded at the deepest points probed. Rate of penetration of ray is drastically reduced in the deep atmosphere.

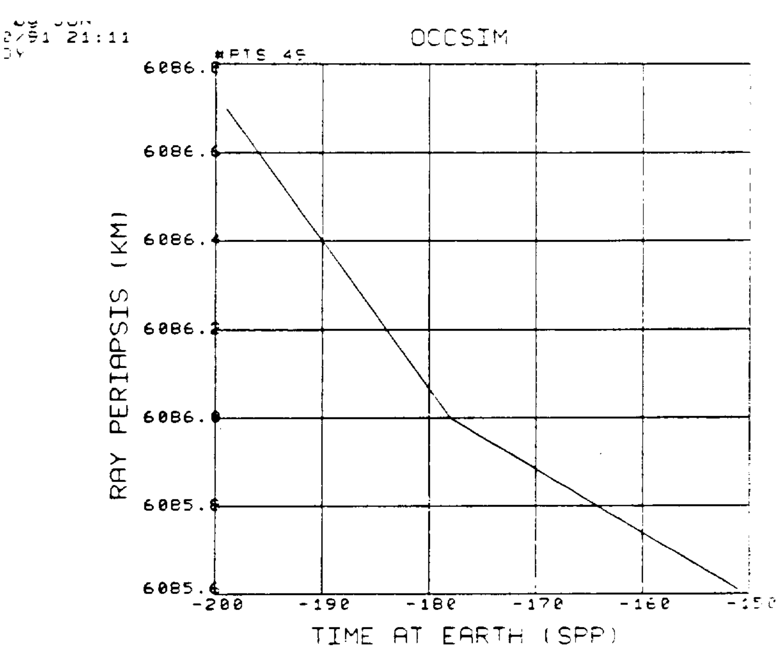
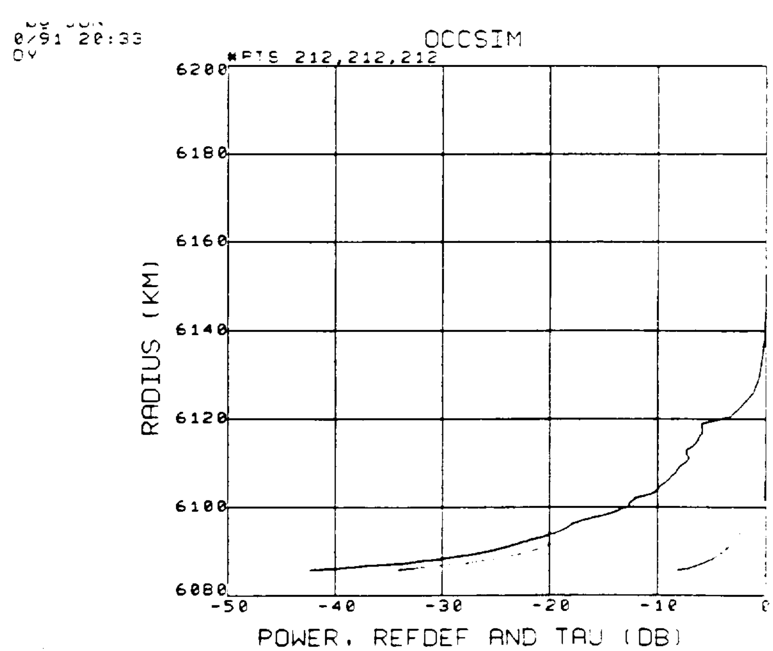


Figure 11: Solid line: Relative amplitude of received signal as a function of depth probed (predicted).
Leftmost dotted line: Refractive defocussing as a function of depth probed
Rightmost dotted line: Atmospheric absorption as a function of depth probed



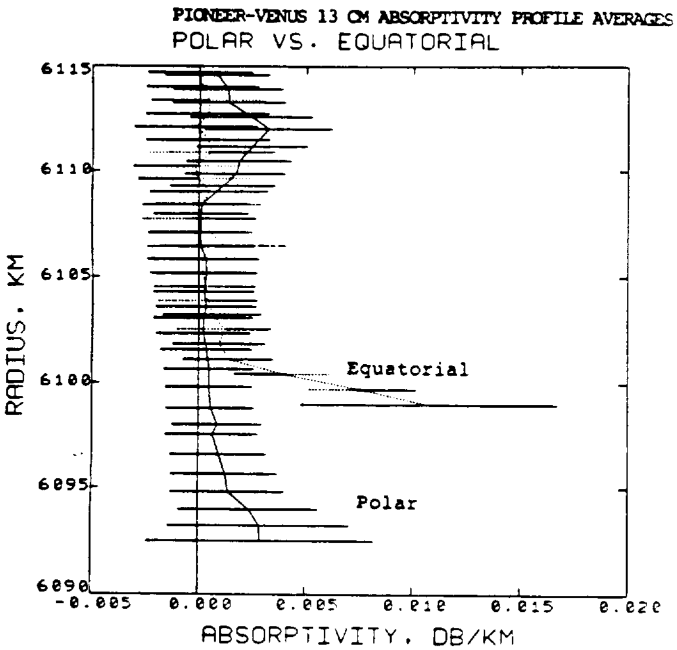


Figure 12: Average 13 cm opacity profiles obtained for the equatorial region (dotted line) and the polar region (solid line) during Season 10*. These absorptivities are related to the abundance of gaseous H_2SO_4. Much deeper profiles could be obtained with much smaller error bars if the Magellan spacecraft were used rather than Pioneer Venus.

*Season 10: 8/86 - 1/87

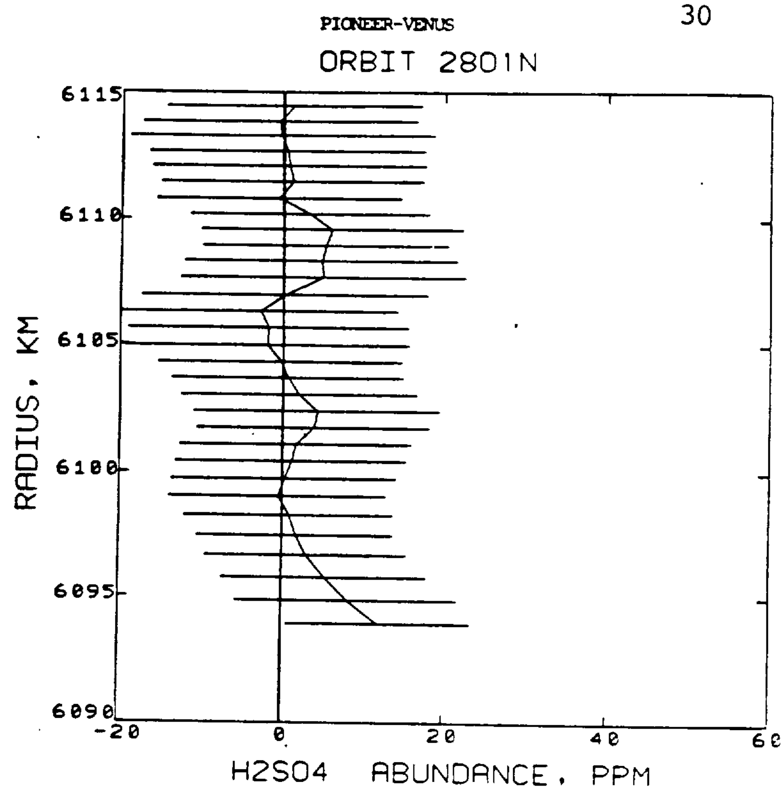
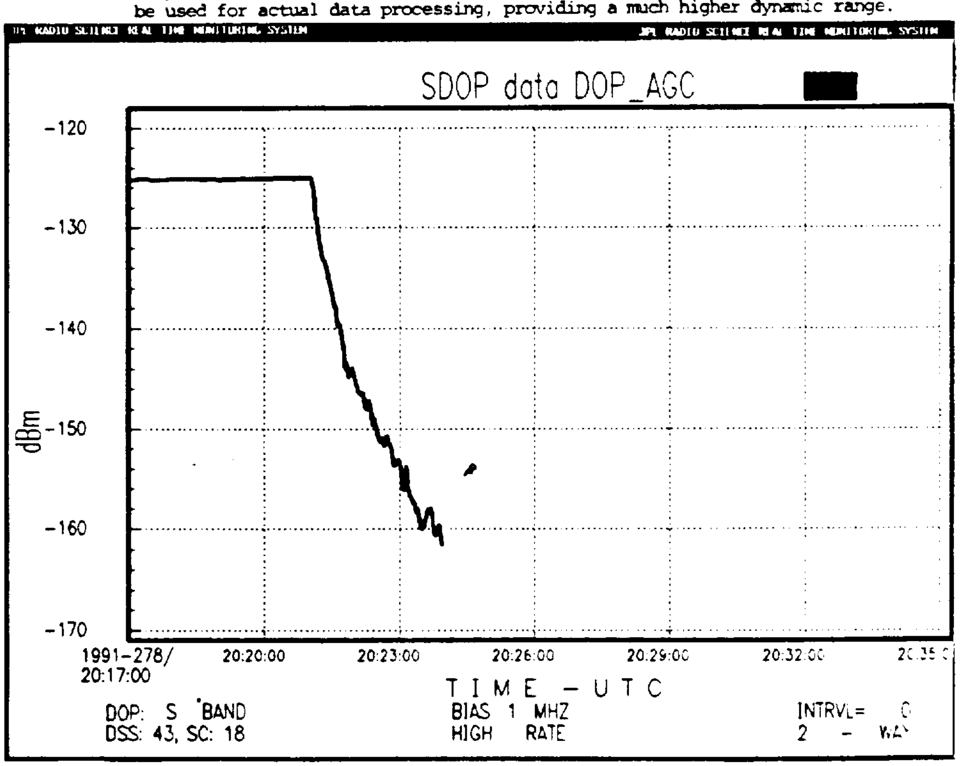


Figure 13: Gaseous H_2So_4 abundance as a function of rad measured for orbit 2801N, which occurred on August 1986 at 40.8•N (solid line) and the abundance expec from saturation vapor pressure (dotted line). The relatively large error bars could be reduced by using the Magellan orbiter. Likewise, the profile could be extended several kilometers deeper.

Figure 14: Actual received signal amplitude measured during Magellan Radio Occultation Experiment using the "closed loop" (lower sensitivity) receiver at DSS-43. (Compare with figure 8). A more sensitive "open loop" receiving system will be used for actual data processing, providing a much higher dynamic range.



UPDATE

MAGELLAN RADIO OCCULTATION EXPERIMENT

5 OCT 91 - 6 OCT 91

DEEPEST ALTITUDE PROBED (13 CM- WAVELENGTH/ S-BAND): 33.5 KM*

DEEPEST ALTITUDE PROBED (3.6 CM- WAVELENGTH/ X-BAND): 34.8 KM*

(*RELATIVE TO MEAN VENUS RADIUS OF 6052 KM)

MAXIMUM BENDING ANGLES MEASURED:

S-BAND: 16 DEGREES

X-BAND: 11.5 DEGREES

MAGELLAN CYCLE 3 -- APOAPSIS RADIO OCCULTATION EXPERIMENTS (Now thru Mar 10)

1. Data taken at DSN with no changes in spacecraft operation.
2. Experiment will only be conducted at X-band (3.6 cm) and with no limb-tracking maneuver. Hence, the signal will only be received down to an altitude of about 65 km, before it is lost due to ray path bending moving the ray out of the main beam of the spacecraft antenna.
3. Initial trials (upload 2038) will probe latitudes from -88°S up to -78° S. Data will be taken with closed loop receiver.
4. The second trial (upload 2052) will probe latitudes from -31°S to the equator. The open loop receiver will also be available for these measurements. (Configuration will allow efficient storage of longer data.)
5. The main science product will consist of vertical profiles of atmospheric refractivity, which is related to the atmospheric temperature-pressure profile. It will provide important information about southern hemisphere middle atmosphere dynamics.

MAGELLAN CYCLE 4 -- APOAPSIS RADIO OCCULTATION EXPERIMENTS (11/18/92-12/31-92)

1. Experiment to be conducted at both S-band (2.3 GHz) and X-band (3.6cm) with spacecraft tracking the limb of the planet using a fitted turn (Similar to the Oct 1991 experiment) rather than using MQPC.

2. The experiment will require 70-m DSN support, and will require data recording for about 16 minutes per occultation. (DSP/open loop receiver)

3. Complete profiles of refractivity (related to atmospheric temperature and pressure, as well as to ionospheric density) and absorptivity (related to abundance of gaseous H_2SO_4) will be obtained for latitudes from -88°S to equatorial, and down to altitudes of 33 km.

4. This study will be the first extended study of the Southern Hemisphere's atmosphere.

APPENDIX II: Abstracts of other papers given at 1991 DPS/AAS Meeting.

01.19-P

Search for H_2S on Jupiter at millimeter wavelengths: Observations and Laboratory Measurements

J. Joiner, P. G. Steffes (Georgia Institute of Technology)

Sulfur has not yet been detected on the Jovian planets. Radiative transfer models suggest that millimeter wavelength pressure-broadened H_2S lines might be detectable on Jupiter. Therefore, we attempted to detect the 1.4 mm (217 GHz) H_2S line using the 10.4 m Caltech Submillimeter Observatory (CSO). Although we were unable to detect H_2S, we were able to obtain a reliable brightness temperature of Jupiter using Mars as the calibration standard.

The spectral resolution of conventional millimeter receivers ($\Delta\nu/\nu = 1 \times 10^{-4}$) is too high for detecting pressure-broadened H_2S lines ($\Delta\nu/\nu = 0.1$). We therefore operated the CSO receiver (DSB with 500 MHz total bandwidth and 2.8 GHz side band separation) as a photometer to measure the differential emission between two frequencies, one near the line center (LO = 215.3 GHz, 1.31 mm) and one off the line center (LO = 229.6 GHz, 1.39 mm). Our observed Jovian brightness temperatures at the two frequencies were 175.0 $\pm$ 2.5 and 178.1 $\pm$ 13, respectively. We are unable to place a tight upper limit on Jupiter's H_2S abundance due to the large uncertainties.

We have also completed a laboratory measurement of H_2S absorption at 1.4 mm in a simulated Jovian atmosphere. The measured hydrogen-broadened linewidth of the $J'_{K'_{-1}K'_{+1}} - J_{K_{-1}K_{+1}} = 2_{0,2} - 2_{1,1}$ H_2S line was 2.0 $\pm$ 0.5 GHz/bar (2.6 $\pm$ 0.7 MHz/torr).

This work was supported by NASA grant NAGW-533. This material is also based on work supported by the Georgia Tech Space Grant Consortium.

20.01

Correlation of Earth-Based NIR Imagery and Pioneer-Venus Orbiter Imagery and Data

B. Ragent (SJSUF), L. Travis (NASA/GISS), D. Crisp (JPL/CIT), D. Allen (AAO), P. Steffes, J. Jenkins (GIT), G. Deardorff, Y. Hung (Sterling)

Dark side images of Venus at wavelengths near 1.7 and 2.3 microns have been obtained at a number of observatories during periods near the past few inferior conjunctions, as well as from the Galileo spacecraft in February, 1990. Favorable viewing opportunities during some of these periods also allowed at least partial images at shorter wavelengths and other data to be obtained from experiments aboard the Pioneer-Venus Orbiter (PVO). Comparisons of these different sets of images help to describe the morphology of cloud structures and regions of atmospheric activity. PVO radio transmitter occultation measurements obtained during the period near the 1991 inferior conjunction will yield vertical profiles of sulfuric acid vapor concentrations in regions near the base of the clouds. Variations in opacities in the near-ir images are presumably due to variations in the number density of large particles in the lower regions of the clouds. Anticorrelation of these opacities with the variation in sulfuric acid concentration from equilibrium values will argue strongly that the large particles are composed of sulfuric acid.

20.10

Laboratory Measurements of the Millimeter-Wave (3 mm) Opacity of Gaseous SO_2 under Simulated Conditions of the Middle Atmosphere of Venus.

A.K. Fahd, P.G. Steffes (Georgia Institute of Technology)

Gaseous sulfur dioxide has long been recognized as one of the dominant absorbers in the Venus atmosphere at microwave frequencies (f< 30 GHz). However, its effect on the millimeter-wave emission is not fully understood. This is due to the lack of any measurements of its opacity at millimeter-wavelengths (shorter than 1 cm). Previously, researchers (Steffes & Eshleman, Icarus 1981, and Janssen & Poynter, Icarus 1981) have reported that the absorption coefficient of gaseous SO_2 in a CO_2 atmosphere was consistent with an f^2 (f=frequency) dependence from 1 to 6 atmospheres. Recently, Fahd & Steffes (DPS, 1990) showed that the f^2 dependence may be valid for frequencies at which the measurements were made, however, the simple extrapolation of SO_2 absorptivity to a higher frequency region (millimeter wavelengths) using the f^2 dependence is not valid, thus the need for a laboratory measurement. The experimental configuration used to measure the SO_2 opacity in a CO_2 atmosphere consists of a Fabry-Perot resonator operating at 94 GHz. The absorptivity of SO_2/CO_2 is measured by monitoring the effects of the gas mixture on the resonant frequency and the bandwidth of the resonator. The results of our measurements show a close agreement with the absorbtivity predicted from a Van Vleck-Weisskopf (VVW) formalism and show a deviation from the f^2 dependence proposed by other researchers. In short, this work has demonstrated that the Van Vleck-Weisskopf formalism appears to provide a good estimate of the absorption of SO_2 in a CO_2 atmosphere at millimeter wavelengths in contrast to the f^2 dependence previously suggested. In addition, our results are incorporated into a radiative transfer model to infer a new abundance profile of gaseous SO_2 in the middle atmosphere of Venus based on existing microwave emission of Venus. Finally, the developed model is used to determine the effects of gaseous SO_2/CO_2 mixture on the millimeter-wave spectrum of Venus.

* This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.

20.14-P

Comparison of Kalman and Wiener Filtering Techniques for Processing Pioneer Venus Radio Occultation Data

J.M. Jenkins, and P.G. Steffes (Georgia Institute of Technology)

Reduction of amplitude data from radio occultation experiments to yield vertical profiles of atmospheric absorptivity involves the application of an Abel-type inverse transform. Because the inverse Abel transform (IAT) is weakly ill-posed (under a change of variables it corresponds to half-order differentiation) the data must be smoothed prior to application of the transform. Otherwise, the IAT amplifies random noise preferentially above the actual signal in the noise-corrupted data. In this study, three techniques are applied to synthetic radio occultation data for comparison: a Kalman filter approach (Hansen and Law, 1985), a Wiener filtering approach (Anderssen, 1976) and a least-squares polynomial approach (Minerbo and Levy, 1969). The results of each method are compared for stability and absolute accuracy against a model atmosphere. In addition to yielding stable results without oversmoothing, the Kalman and Wiener filtering techniques hold potential to reduce estimated uncertainties on derived profiles. Results of applying these methods to actual radio occultation data from Pioneer Venus obtained during Season 10 (1986-87) are also presented.

* This material is based on work supported in part under a National Science Foundation Graduate Fellowship.

APPENDIX III: Paper presented at the Third International Conference on Laboratory Research for Planetary Atmospheres.

LABORATORY MEASUREMENT OF THE MILLIMETER-WAVE OPACITY OF GASEOUS SULFURIC ACID (H_2SO_4) UNDER VENUS-LIKE CONDITION.

A.K. Fahd, P.G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Ga. 30332

Recent observations of the millimeter-wave emission from Venus at 115 GHz (2.6 mm) have shown significant variations in the continuum flux emission (de Pater et al., Icarus 1991) which may be attributed to the variability in the abundances of the absorbing constituents in the middle atmosphere of Venus. Such constituents include gaseous H_2SO_4 ,SO_2 , and liquid sulfuric acid (cloud condensates). Recently, Fahd and Steffes (DPS 91, and JGR (Planets) 1991) have shown that the effects of liquid H_2SO_4 and gaseous SO_2 cannot completely account for this measured variability in the millimeter-wave emission of Venus. To fully understand potential sources of this variation, one needs to study the effects of gaseous sulfuric acid on the emission of Venus. However, the determination of the millimeter-wave opacity of gaseous H_2SO_4 is difficult since no laboratory measurements have been performed for Venus-like conditions. As a result, the laboratory measurements of the opacity of gaseous sulfuric acid in a CO_2 atmosphere at millimeter-wavelengths are greatly needed. Laboratory measurements of the opacity of gaseous sulfuric acid in a CO_2 atmosphere are currently being performed at 94 GHz. The experimental setup employs a free-space transmission configuration. The cell containing the gaseous mixture is placed in a temperature controlled chamber. The opacity of the gas mixture is measured at 550, 570 and 590 K for 1 and 2 Atm total pressure. The results will then be fitted to a model to account for the opacity of the gas mixture in the millimeter-wave region. This will then be incorporated into a radiative transfer model to interpret the measured variations in the millimeter-wave emission of Venus.

* This work is supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.